Energy-Aware Broadcasting and Multicasting in Wireless Ad Hoc Networks:

A cross-layering approach

Jeffrey E. Wieselthier

Gam D. Nguyen

Information Technology Division

Naval Research Laboratory

Anthony Ephremides

Electrical and Computer Eng. Dept.

University of Maryland

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Abstract

The wireless networking environment presents formidable challenges to the study of broadcasting (one-to-all) and multicasting (one-to-many) problems, especially when energy-aware operation is required. To address the specific problem of energy-aware tree construction in wireless ad hoc networks, we have developed the Broadcast Incremental Power (BIP) and Multicast Incremental Power (MIP) algorithms. Our algorithms are based on a cross-layering approach in which tree structure and communication range are chosen jointly.

We describe the similarities and differences between energy-limited and energy-efficient modes of operation, and we illustrate the impact of these overlapping (and sometimes conflicting) considerations on network operation. Examples of energy-limited applications include sensor networks and military networks in which soldiers' batteries cannot be recharged during a mission. When such constraints are present, fundamental objectives include the maximization of a network's useful lifetime and the maximization of traffic volume that is delivered during this lifetime. Additionally, we extend our model to exploit the properties of directional antennas to obtain further performance improvement.

Energy-Aware Networking

Energy-Efficient vs Energy-Constrained

- **Energy-Efficient**
  - Energy is a cost (e.g., to replace batteries)
    - Minimize energy to achieve given communication goals
- **Energy-Constrained**
  - Energy is a constraint
    - A node dies when its energy is depleted
      - Sensor networks
      - Ad hoc networks in which batteries can't be recharged or replaced
  - **Goals:**
    - Maximize network's useful lifetime
    - Maximize quantity of data delivered to destinations

Optimizing energy efficiency does NOT guarantee good performance in energy-constrained applications!

A networking problem:

Energy-Efficient Multicasting in Ad Hoc Wireless Networks

Non-Wireless

- Find **trees** to minimize number of transmissions (or other cost function) in a **fixed graph**

Wireless Ad Hoc (Infrastructureless)

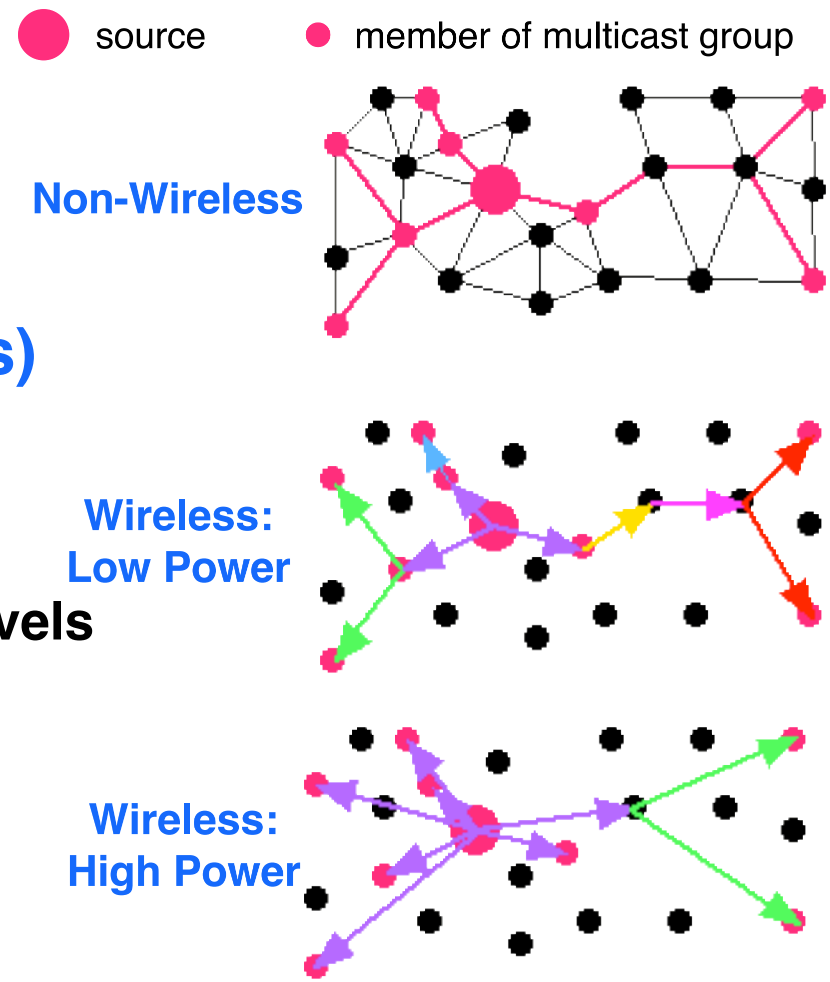
- **Fundamental trade-offs**
  - Reach vs interference
  - Reach vs energy expenditure
- Connectivity depends on RF power levels

$$p = r^{\alpha} \qquad (p < p_{max})$$

we assume that RF power is continuously adjustable

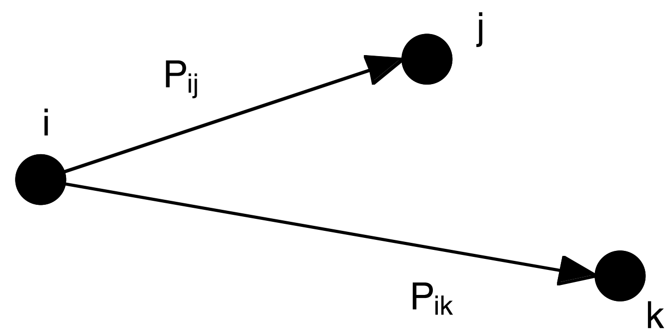
Broadcasting

- A special case of multicasting in which all nodes are members of multicast group



An Important Energy-Related Property of Wireless Networks

The "Wireless Multicast Advantage"



- A wireless transmission reaches all of its neighbors
  - (Assuming use of omnidirectional antennas)
  - $P_{i,(j,k)} = \max \{ P_{ij}, P_{ik} \}$ — "Node-based" costs: Max
- Cost in wired networks
  - $D_{i,(j,k)} = D_{ij} + D_{ik}$ — "Link-based" costs: Additive

Wireless vs Wired Networks

Wired Networks	Wireless Networks
Well-defined graph	Connectivity determined by transmitted power
Well-defined link capacities	A node's capacity can be allocated to form links with its neighbors
Well-defined link costs	Costs are node-based
No interference between links	Frequencies must be coordinated
Link-Centric	Node-Centric

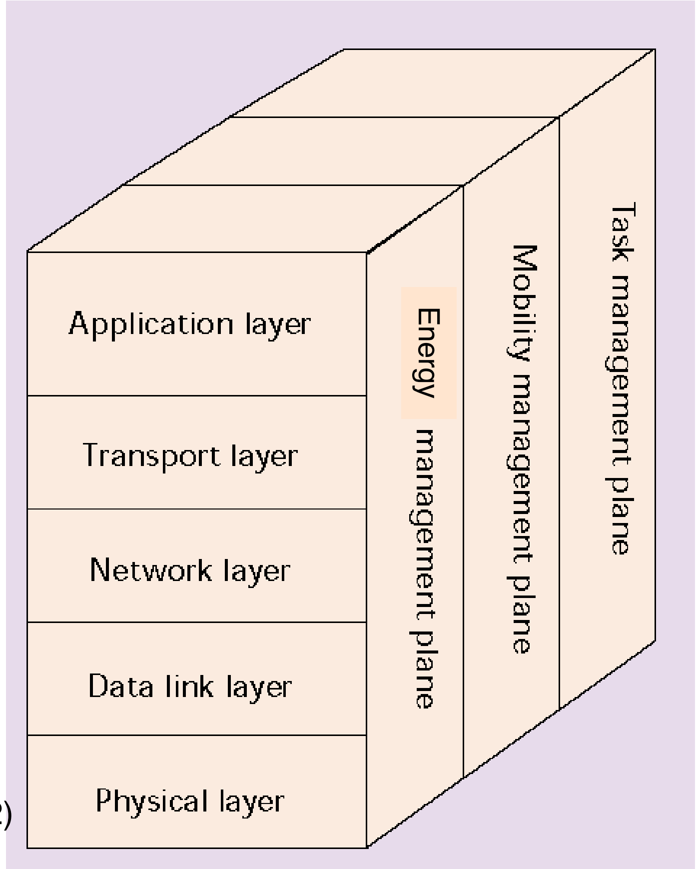
- Wireless networks are different!
  - Novel approaches must be developed
    - Can't simply apply techniques developed for wired networks

Energy-Related Issues Create a Dependence Among Network Functions

- Media access control (MAC)
- Routing
- Network self-organization
- Network performance

Energy-aware operation

Cross-Layer Design



(Ref: Akyildiz et al, 2002)

- **A major cross-layer issue:**
  - **How to allocate the available energy among sensing, signal processing, and communication**
    - **both for network longevity and mission performance**

Optimal Broadcast and Multicast Trees
(Energy-Efficient Case)

What to optimize?

- Minimize energy expenditure of tree for each request
  - Source node becomes root of tree

What's new?

- Properties of ad hoc wireless networking environment

Complexity

- Wired Networks
  - Broadcasting: Minimum-Cost Spanning Tree (Polynomial $O(N^2)$)
  - Multicasting: Steiner Tree (NP-Complete)
- Wireless Networks
  - Broadcasting: No polynomial algorithms available
    - NP-Complete ⇨ heuristics are needed
  - Multicasting: Certainly at least as difficult as broadcasting

Our Approach

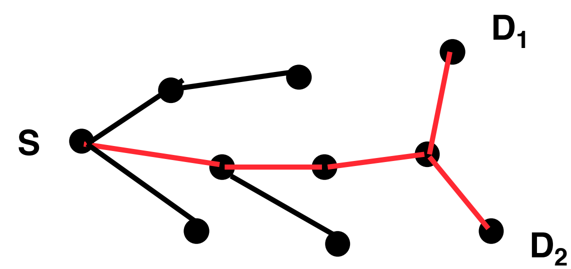
1) Find minimum-power broadcast tree

- ☞ **Broadcast Incremental Power (BIP) Algorithm**
  - — suboptimal

- ❖ **Similar to Minimum-cost Spanning Tree (MST) Problem**
  - ❈ Finding MST is easy for link-based (wired) networks
  - ❈ Difficult (NP-complete) for node-based (wireless) networks
- ❖ **BIP is similar to Prim's algorithm**
  - ❈ But uses incremental cost when new nodes are added
  - ❈ BIP is node-based

2) "Prune" the tree produced by BIP

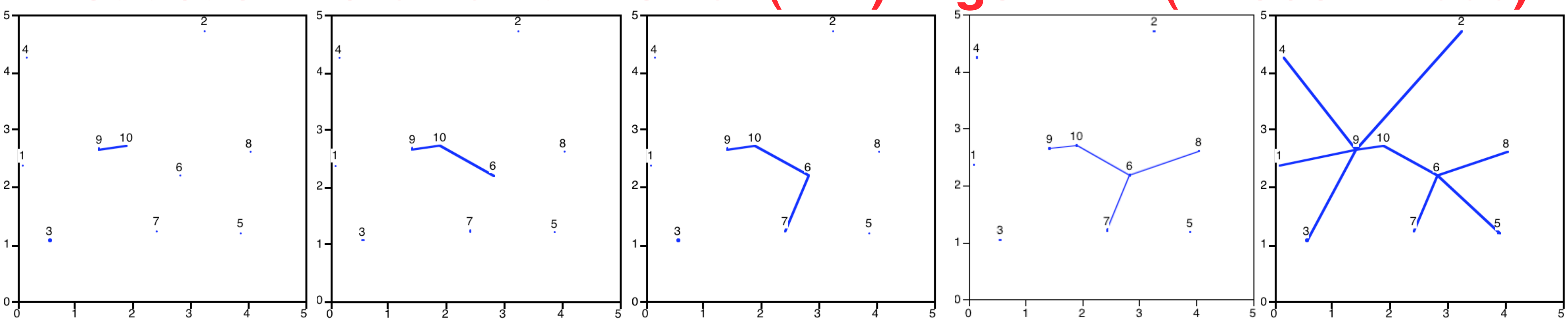
- ☞ **Multicast Incremental Power (MIP)**



3) "Sweep" to eliminate unnecessary transmissions

The Incremental Cost Principle for Energy-Efficient Broadcast Trees

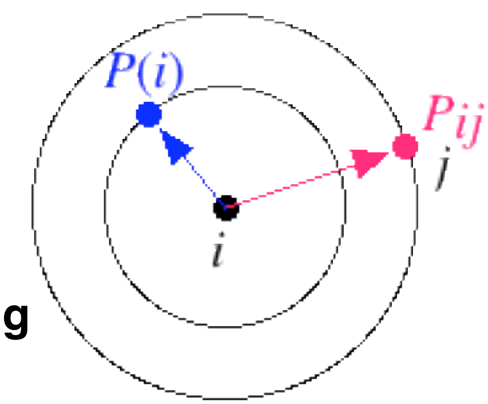
Broadcast Incremental Power (BIP) Algorithm (Infocom 2000)



Step 1: 10 --> 9 | Step 2: 10 --> 6 | Step 3: 6 --> 7 | Step 4: 6 --> 8 | Final Tree

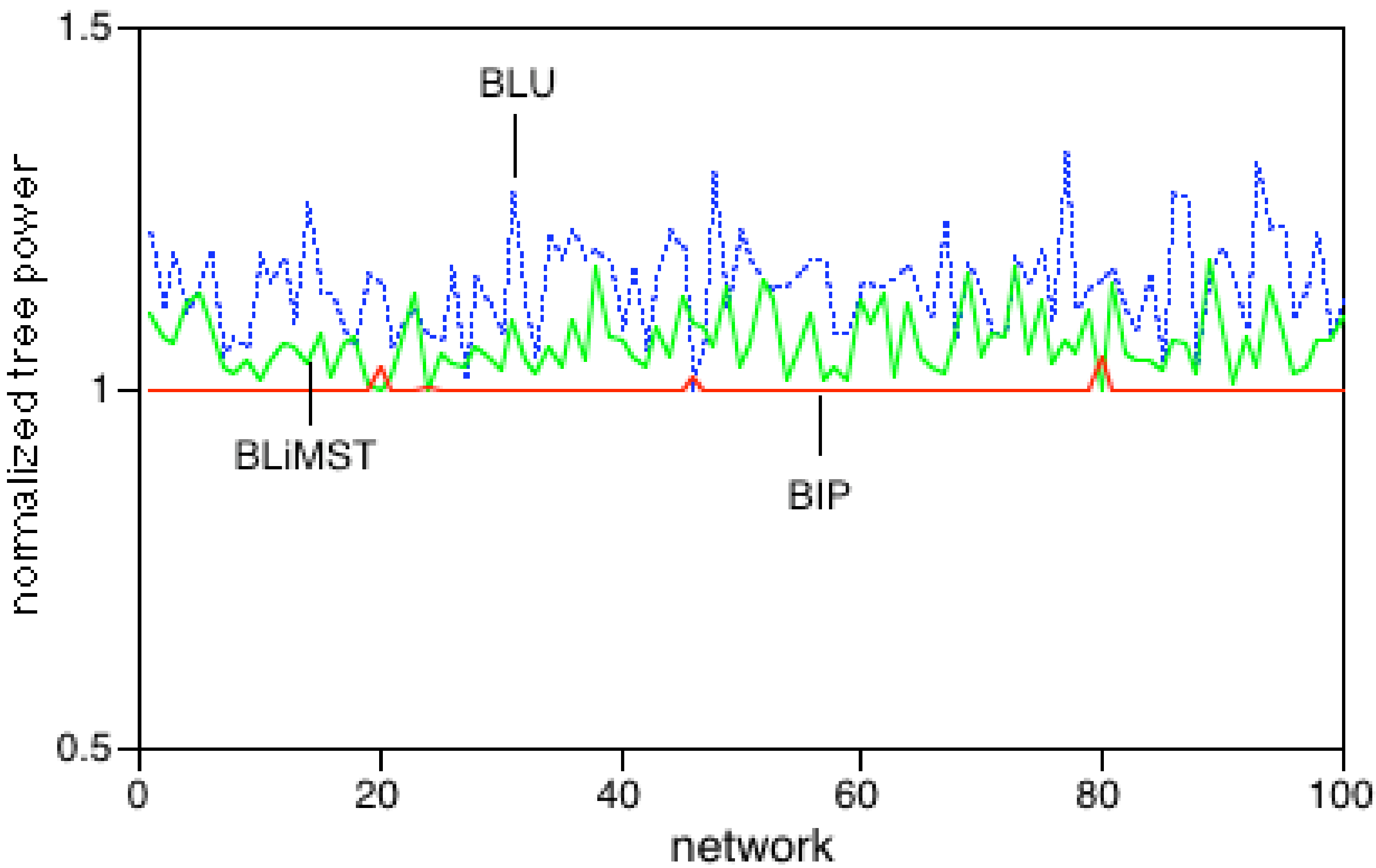
A node-based minimum-cost spanning tree algorithm

- **Start with only the Source node (10) in the tree**
- **At each step, add the node that can be added using the smallest incremental power**
  - **Additional power for Node i to reach new Node j**
    - $P'_{ij} = P_{ij} - P(i)$
      - P_{ij} = **Power required for Node i to reach Node j**
      - $P(i)$ = **Power at which Node i is already transmitting**



BIP Provides Improved Energy Efficiency

Example: 100 different 100-node networks; Group size = 100



BIP is best for almost all network examples

BLU and BLiMST are "conventional" algorithms that do not incorporate the properties of the wireless channel

Hard Constraints on Energy

- A node "dies" when its battery is fully depleted
- ☞ How can we extend the network's useful lifetime?
  - e.g., time that first node dies

Re-define link costs:

$$C_{ij} = P_{ij}\left(\frac{E_i(0)}{E_i(t)}\right)^{\beta}$$

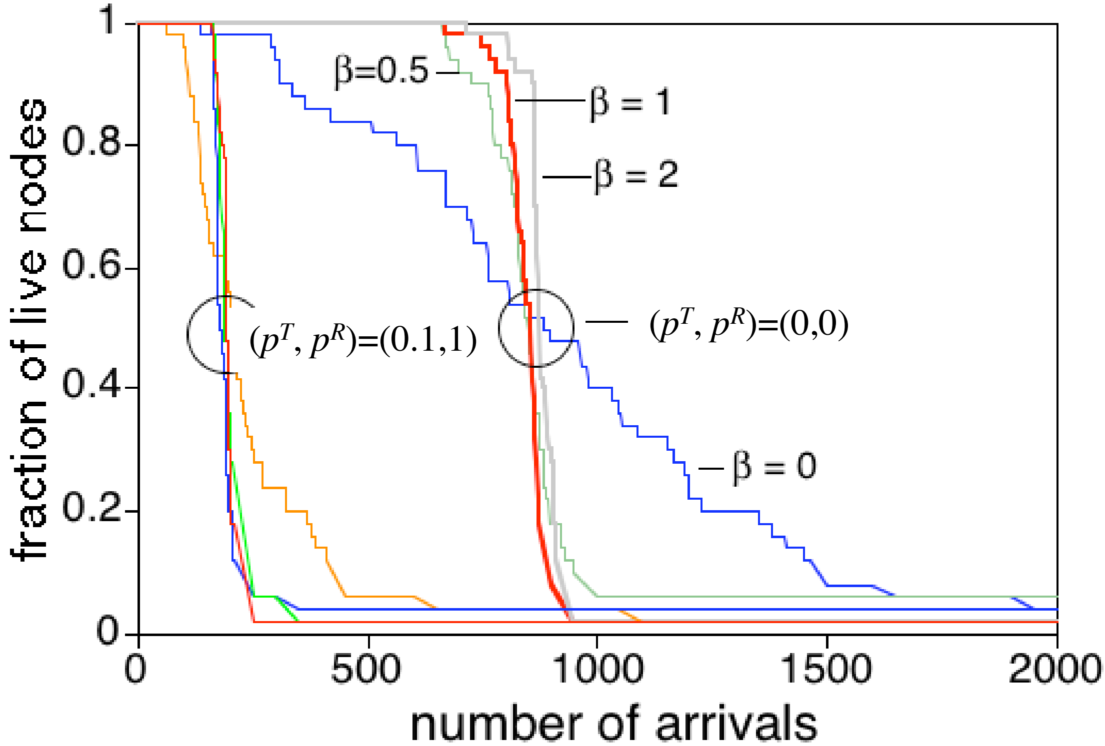
- P_{ij} = link power, $E_i(t)$ = residual energy at Node i at time t

- ☞ Choose value of β to discourage use of nodes with little residual energy

Note: We use a simplified model, under which each node initially has energy $E_i(0)$. We neglect the fact that the total energy that a battery can deliver is based on its discharge/recovery pattern.

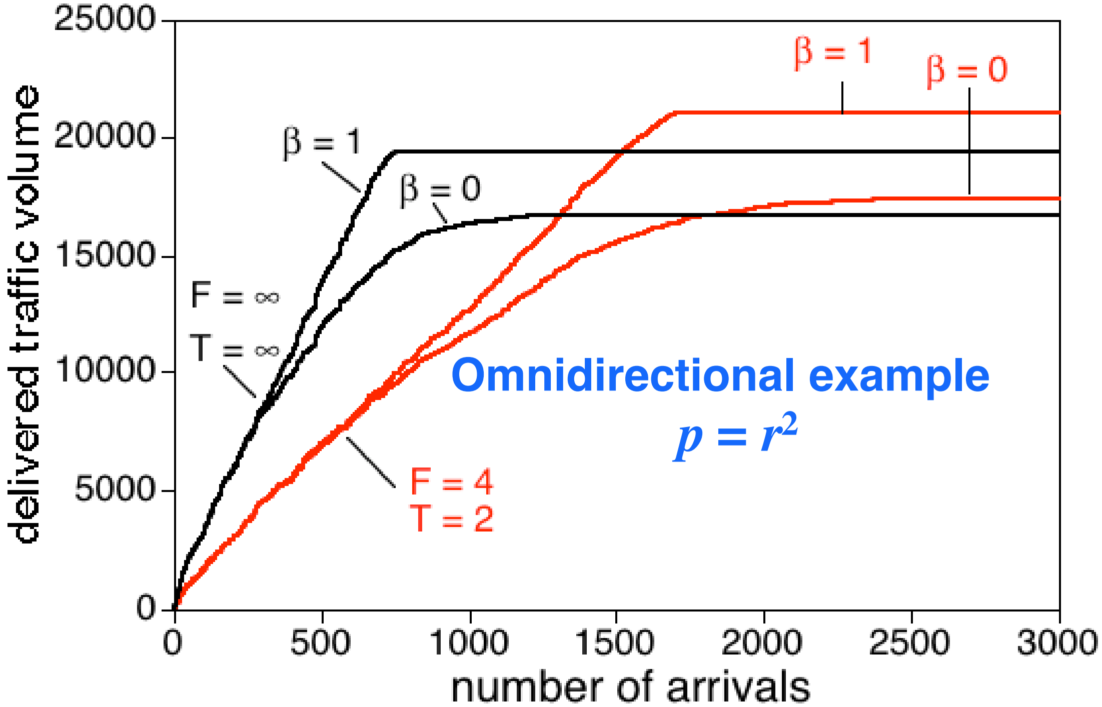
Extend Network Lifetime (MIP)
via choice of β

50-node network;
Multicast groups randomly chosen with between 1 and 49 destinations;
(p^T, p^R) = (Transmitter signal-processing power, Receiver signal-processing power)



- **0.5 ≤ β ≤ 2**
  - **Delays death of first node significantly**
  - **Keeps most (80% to 90%) nodes alive longer**
- **Impact of high levels of signal-processing power** ((p^T, p^R) = (0.1, 1.0))
  - **Nodes die much sooner, but same qualitative behavior**

Impact of β > 0 and Finite Resources (MIP)



β > 0

- Significantly delays death of first node
- Keeps 80–90% of nodes alive much longer
- Increases overall traffic volume
- Near-constant rate of traffic delivery until network dies

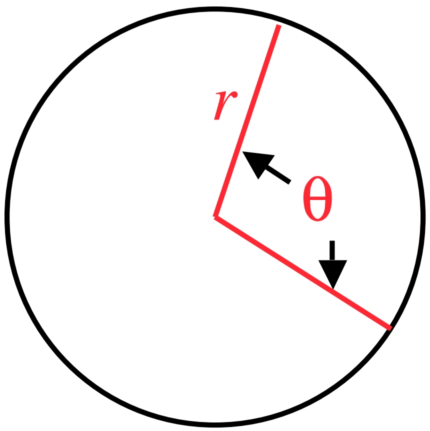
Finite Resources

- Lowers rate of traffic delivery
- But may result in greater overall delivered traffic volume

Why Directional Antennas?

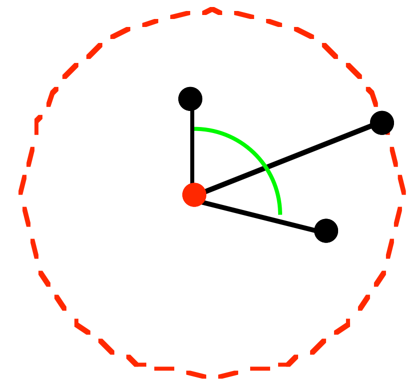
Concentrate energy where needed

$$p^{RF}(r,\theta) \propto \frac{\theta}{360} r^{\alpha} \qquad 2 \le \alpha \le 4$$



- **Reduce energy expenditure**
  or
  Extend communication range
- **Reduce interference**

Algorithms for Directional Antennas



DA1: Reduced-Beam BIP (RB-BIP)

- Construct broadcast tree using BIP
- Reduce the beamwidth at each transmitting node

DA2: Directional BIP (D-BIP)

- At each step, find the pair (θ, r) that minimizes the incremental cost
  - Two basic possibilities:
    - Former leaf node will transmit
    - An already transmitting node will do one or more of the following:
      - Increase its power (r)
      - Increase its angle (θ)
      - Shift the beam
    - DA2 is more complex than DA1

Multicasting:

- First find broadcast trees using RB-BIP or D-BIP
- Then prune, resulting in RB-MIP or D-MIP

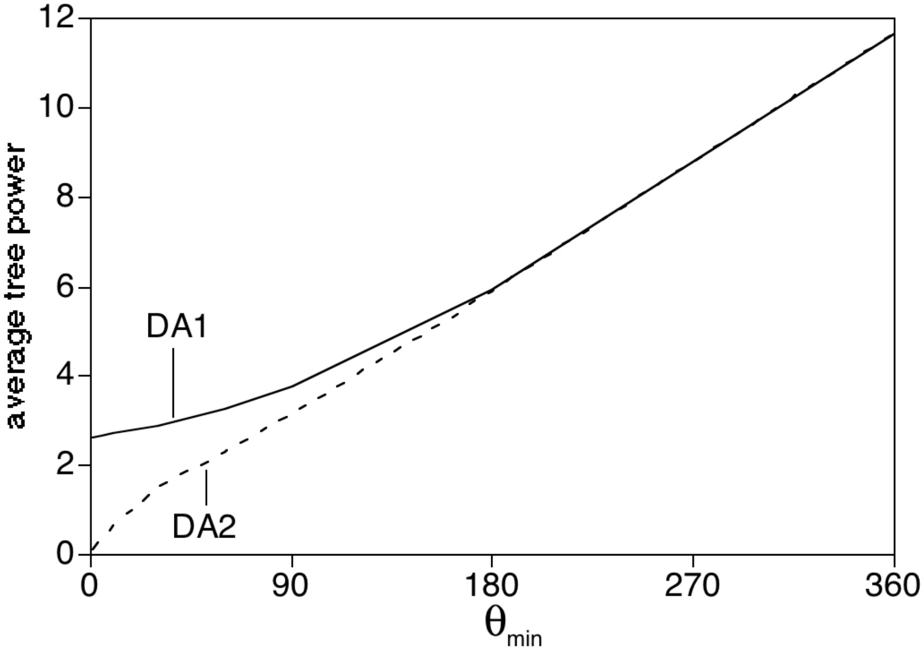
Networking Techniques That Exploit Directional Antennas Provide Improved Energy Efficiency

DA1: RB-BIP; DA2: D-BIP

50-node network; $\alpha = 2$; $p^T = p^R = 0$

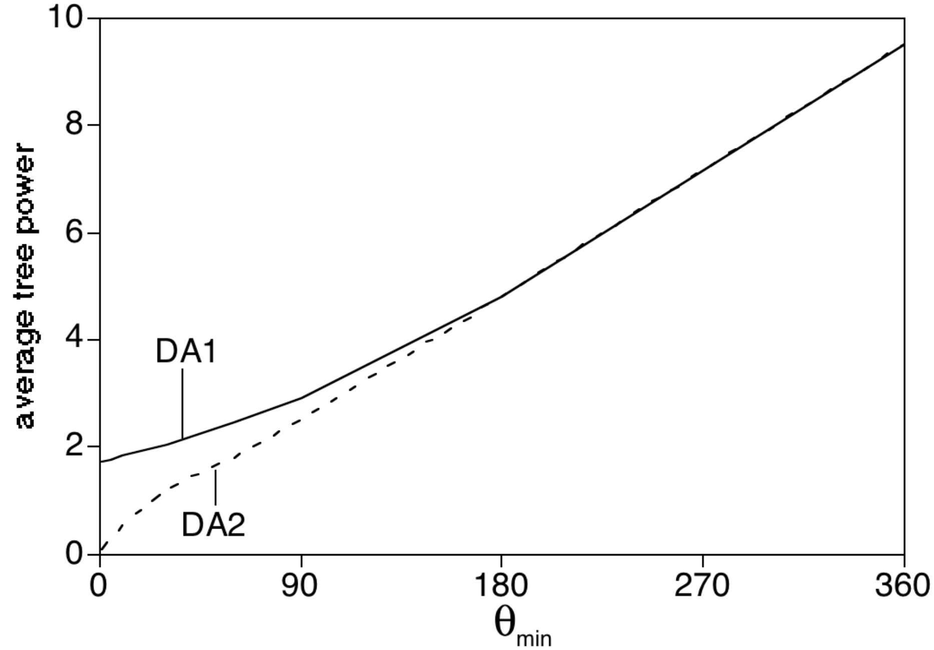
Broadcasting

RB-BIP & D-BIP



Multicasting

RB-MIP & D-MIP

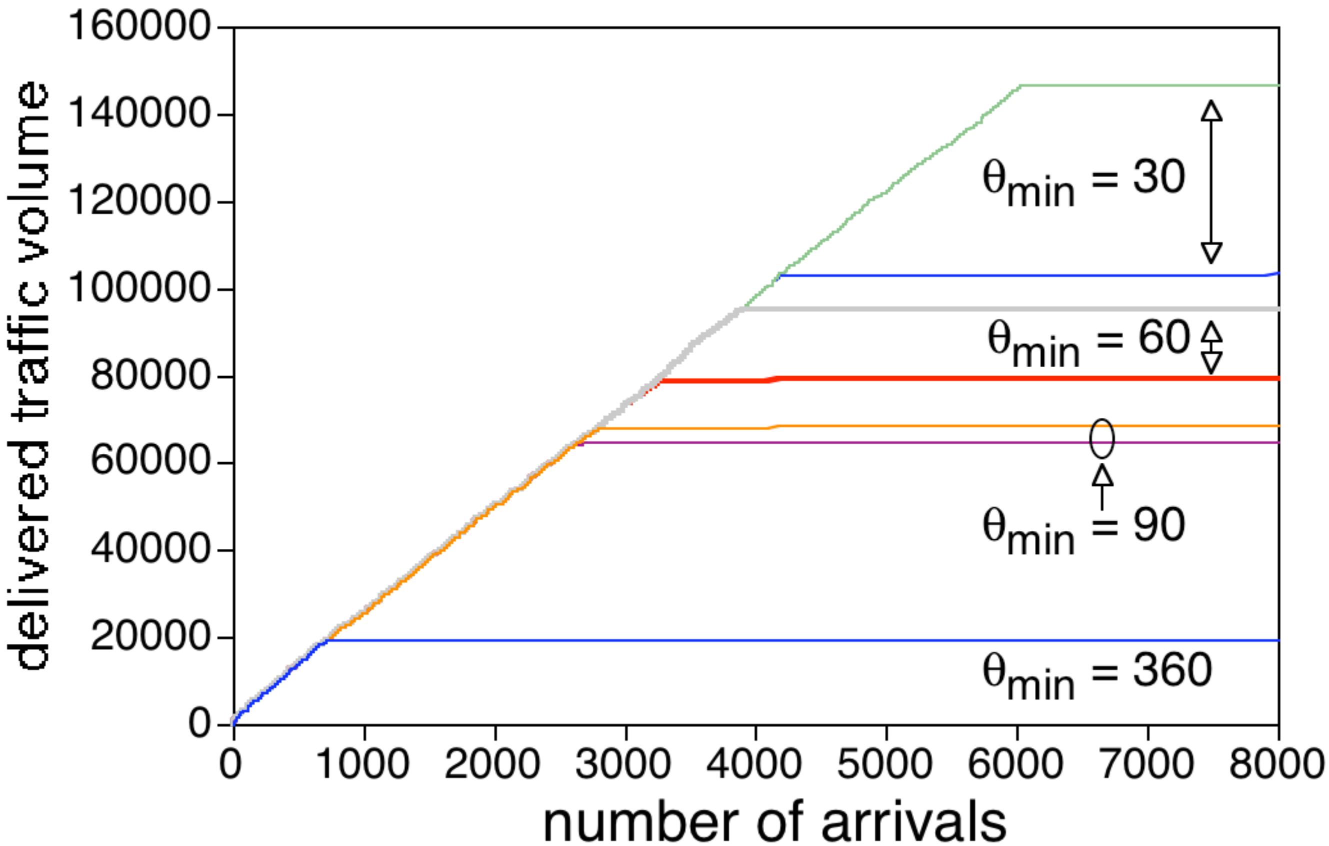


Size of multicast groups is uniformly distributed between 2 and 50

- **Use of directional antennas provides considerable power reduction**
- **Especially D-BIP when $\theta_{min} < 90$**

Networking Techniques & Directional Antennas Increase Network Lifetime and Traffic Volume

50-node network; finite energy at each node; $\alpha = 2$; $\beta = 1$



For each value of θ:

Lower curve: RB-MIP

Upper curve: D-MIP

Curves stop increasing when network dies

- **Delivered traffic volume increases as θ_{min} decreases**
- **Advantage of D-MIP increases as θ_{min} decreases**

Summary and Conclusions

- **Two modes of energy-aware networking**
  - **Energy efficient**
  - **Energy constrained**
- **Properties of wireless medium should be exploited in network design**
  - **Vertical coupling of protocol layer functions**
    - **e.g., how to allocate energy among sensing, signal processing, and communication**
- **BIP and MIP algorithms provide improved energy-aware performance**
  - **Developed for energy-efficient operation**
  - **Adapted for energy-constrained operation**
- **Directional antennas**
  - **Provide further improvement in energy-aware performance**
  - **Can be exploited in design of networking algorithms**

☞ **Networking techniques can greatly improve energy efficiency and/or network lifetime**

- **Improved energy sources are NOT the only way to address energy issues**

Journal Articles on Energy-Aware Networking

[1] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Algorithms for Energy-Efficient Multicasting in Static Ad Hoc Wireless Networks,” *Mobile Networks and Applications (MONET)*, **6**-3, pp. 251-263, June 2001.

[2] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Energy-Efficient Broadcast and Multicast Trees in Wireless Networks,” *Mobile Networks and Applications (MONET)*, **7**-6, pp. 481-492, December 2002.

[3] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Energy-Efficient Multicasting of Session Traffic in Bandwidth- and Transceiver-Limited Wireless Networks,” *Journal of Cluster Computing*, **5**-2, pp. 179-192, April 2002.

[4] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Resource Management in Energy-Limited, Bandwidth-Limited, Transceiver Limited Wireless Networks for Session-Based Multicasting,” *Computer Networks*, **39**-2, pp. 113-131, June 2002.

[5] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Energy-Aware Wireless Networking with Directional Antennas: The Case of Session-Based Broadcasting and Multicasting,” *IEEE Transactions on Mobile Computing*, **1**-3, pp. 176-191, July-Sept. 2002.